(19) Europäisches Patentamt
European Patent Office
Offic   uropéen des brevets

(11) Publication number: **0 671 372 A2**

EUROPEAN PATENT APPLICATION

(21) Application number: 95103253.1

(22) Date of filing: 07.03.95

(51) Int. Cl.⁶: **C04B 37/04**

(30) Priority: 09.03.94 JP 38734/94

(43) Date of publication of application:
13.09.95 Bulletin 95/37

(84) Designated Contracting States:
CH DE FR GB IT LI NL SE

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(54) **Anodic bonding method and method of producing an inkjet head using the bonding method.**

(57) Disclosed is a method of anodically bonding a silicon substrate (1) to a glasssubstrate (2) wherein the thickness of at least a portion (5) of the silicon substrate (1) is less than the thickness of the glass substrate (2). The method comprises establishing a suitable bonding temperature, heating the substrates to the bonding temperature and applying a voltage between the substrates for a predetermined time. In order to prevent reduced thickness portions (5) of the first substrate (1) from getting warped, the bonding temperature is calculated such that the contraction of the silicon substrate (1) while cooling from the selected bonding temperature to room temperature is equal to or greater than the contraction of the glass substrate (2). The preferred use of this method for manufacturing inkjet heads having electrostatic actuators with such reduced thickness portions (5) serving as vibration plates of the actuators is described.
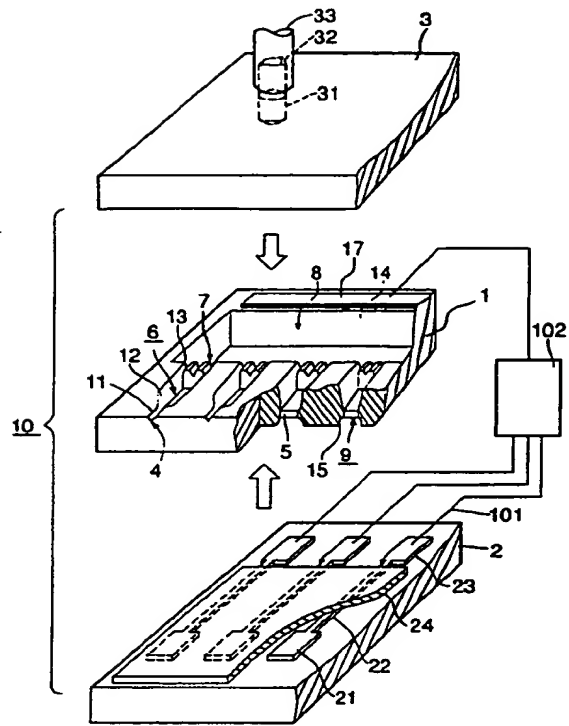
EP 0 671 372 A2

FIG. 2

The present invention relates to an anodic bonding method and to a method of producing an inkjet head using the anodic bonding method.

Anodic bonding as a method for firmly fixing one piece or substrat to another is known. A typical anodic bonding process comprises a first step of heating the substrates to be bonded up to a c rtain bonding temperature, a second step of maintaining the substrates at the bonding temperature for a predetermined first period of time, a third step of applying a high voltage between the substrates for a predetermined second period of time, a fourth step of maintaining the substrates at the bonding temperature for a predetermined third period of time with the voltage removed, and a fifth step during which the bonded substrates cool down to room temperature. An example of the first, second and third periods of time is 10 min, 5 min and 5 min, respectively. When this bonding method is used for combining two substrates of materials differing in their coefficients of linear thermal expansion the different amounts of contraction or shrinkage in the two substrates as they cool down to room temperature may cause undesirable permanent stress in the substrates. This problem is particularly significant where one of the two substrates has portions of reduced thickness and the different contractions of the combined substrates causes these portions to permanently deform or warp.

One example where this problem can cause serious defects is a recently developed type of inkjet head for an inkjet recording apparatus. In this type of inkjet head electrostatic actuators are used to convert electric drive pulses into the pressure pulses required for ejection of ink droplets through respective nozzles of the inkjet head. Inkjet heads of this electrostatically driven type are disclosed in, for example, JP-A-289351/1990, JP-A-80252/1990, EP-A-0 580 283 and in EP-A-0 634 272, EP-A-0 629 502 and EP-A-0 629 503 (the latter three documents forming prior art according to Art. 54(3) EPC).

The inkjet head disclosed in EP-A-0 580 283, for example, comprises three substrates, a first substrate made of Si and second and third substrates made of glass. The first substrate is sandwiched between the second and third substrates and the substrates are anodically bonded to each other. A plurality of separate ink chambers and an associated system of ink supply passages is formed between the first and the third substrate by means of corresponding recesses and grooves etched into the surface of the first substrate prior to the bonding. The bottom of each ink chamber on the side remote from the third substrate forms a vibration plate, i.e., the diaphragm of a respective electrostatic actuator. Associated nozzles electrodes are formed on the surface of the second substrate prior to the bonding. A gap between each diaphragm and the associated nozzle electrode is provided for by a recess etched into either of the opposing surfaces of the first and second substrates.

Anodic bonding is the preferred technique to combine the substrates because it allows to achieve the required bonding strength and the processing precision necessary for the gap between the diaphragms and nozzle electrodes. To improve printer resolution and enable the inkjet head to be driven at the low voltages commonly used in printers, the diaphragms formed in the first substrate must be made thinner than the glass of the second and third substrates on both sides of the of the first substrate. However, when the above mentioned shrinkage of the first substrate including the diaphragms is less than that of the glass substrates, the resulting stress may cause permanent deformation or warp of the diaphragms. This may prevent the inkjet head from functioning normally.

As mentioned before, this problem is not limited to inkjet heads but may occur wherever a first substrate is bonded to a second substrate of a different material having a different coefficient of linear thermal expansion, the first substrate comprises a portion thinner than the adjoining substrate and anodic bonding under a relatively high temperature is employed.

Therefore, the object of the present invention is to provide an anodic bonding method suitable for bonding a first substrates of a first material to a second substrate of a second material wherein the thickness of at least a portion of the first substrate is less than the thickness of the second substrate, which does not suffer from the contraction problem explained above.

Another object of the invention is to provide a method of producing inkjet head having one or more electrostatic actuators wherein anodic bonding is used to combine two or more substrates of the inkjet head without causing deformation or warp of the diaphragms of the one or more actuators.

These objects are achieved with a method as claimed in claims 1 and 2, respectively.

Preferred embodiments of the invention are subject-matter of the dependent claims.

The invention will be explained in more detail below with reference to the drawings in which:

Fig. 1   is a graph showing the relationship between bonding temperature and coefficients of linear thermal expansion;

Fig. 2   is a partially exploded perspective view of an inkjet head to which the present invention is preferably applied;

Fig. 3   is a lateral cross section of the inkjet head shown in Fig. 1;

Fig. 4   is a plan view tak n along lin A-A in Fig. 3;
Fig. 5   is used to describe the anodic bonding process; and
Fig. 6   is used to describe warping of th diaphragms.

For a better appreciation of the present invention and the problem solv d by it, an embodiment of an
5   inkjet head with electrostatic actuators will first be described.

Fig. 2 is a partially exploded perspective view and cross-section of an inkjet head to which the present
invention is applied. While this embodiment is shown as an edge type head wherein ink is ejected from
nozzles provided at the edge of a substrate, the invention may also be applied to a face type head wherein
the ink is ejected from nozzles provided on the top surface of the substrate. The inkjet head 10 of this
10   embodiment is made up of three substrates 1, 2, 3 one stacked upon the other and structured as described
in detail below.

A first substrate 1 is sandwiched between second and third substrates 2 and 3, and is made from a
silicon wafer. Plural nozzles 4 are formed between the first and the third substrate by means of
corresponding nozzle grooves 11 provided in the top surface of the first substrate 1 such as to extend
15   substantially in parallel at equal intervals from one edge of the substrate. The end of each nozzle groove
opposite said one edge opens into a respective recess 12. Each recess in turn is connected via respective
narrow grooves 13 to a recess 14. In the assembled state the recess 14 constitutes a common ink cavity 8
communicating via orifices 7 formed by the narrow grooves 13, and ink chambers 6 formed by the recesses
12 with the nozzles 4. In the present embodiment, each orifice 7 is formed by three parallel grooves 13
20   mainly to increase the flow resistance but also to keep the inkjet head operative if one of the grooves
becomes clogged. As will be understood, the grooves and recesses referred to above can be easily and
precisely formed by photolithographic etching of the semiconductor substrate.

Electrostatic actuators are formed between the first and the second substrate. The bottom of each ink
chamber 6 comprises a diaphragm 5 formed integrally with the substrate 1. A common electrode 17 is
25   provided on the first substrate 1. Borosilicate glass, such as Pyrex glass, is used for the second substrate 2
bonded to the bottom surface of first substrate 1. Nozzle electrodes 21 are formed on the surface of second
substrate 2 by sputtering gold to a 0.1 μm thickness in a pattern essentially matching the shape of
diaphragms 5. Each of nozzle electrodes 21 comprises a lead member 22 and a terminal member 23. A 0.2
μm thick insulation layer 24 for preventing dielectric breakdown and shorting during inkjet head drive is
30   formed from a Pyrex sputter film on the entire surface of the second substrate 2 except for the terminal
members 23. A recess 15 for accommodating a respective nozzle electrode 21 is provided below each
diaphragm 5. Bonding the second substrate 2 to the first substrate 1 results in vibration chambers 9 being
formed at the positions of recesses 15 between each diaphragm 5 an the corresponding nozzle electrode
21 opposite to it. In this embodiment, recesses 15 formed in the bottom surface of the first substrate 1
35   provide for gaps between the diaphragms and the respective electrodes 21. The length G (see Fig. 3;
hereinafter the "gap length") of each gap is equal to the difference between the depth of recess 15 and the
thickness of the electrode 21. It is to be noted that this recess can be alternatively formed in the top surface
of the second substrate 2. In this embodiment, the depth of recess 15 is 0.6 μm, and the pitch and width of
nozzle grooves 11 are 0.72 mm and 70 μm, respectively.

40   As with second substrate 2, borosilicate glass is used for the third substrate 3 bonded to the top
surface of first substrate 1. Bonding third substrate 3 to first substrate 1 completes formation of nozzles 4,
ink chambers 6, orifices 7, and ink cavity 8. An ink supply port 31 is formed in third substrate 3 so as to
lead into ink cavity 8. Ink supply port 31 is connected to an ink tank (not shown in the figure) using a
connector pipe 32 and a tube 33. Ink cavity 8 and orifices 7 serve as ink supply passage for supplying ink
45   to the individual ink chambers 6.

First substrate 1 and second substrate 2 are anodically bonded at 270°C to 400 $^\circ$C by applying a
voltage of 500 V to 800 V, and first substrate 1 and third substrate 3 are bonded under the same conditions
to assemble the inkjet head as shown in Fig. 3. This bonding will be discussed in detail below. After
bonding the substrates, gap length G between diaphragms 5 and nozzle electrodes 21 is 0.5 μm in this
50   embodiment. The distance G1 between diaphragms 5 and insulation layer 24 covering nozzle electrodes 21
is 0.3 μm.

The thus assembled inkjet head is driven by means of a drive unit connected by leads 101 to common
electrode 17 and terminal members 23 of nozzle electrodes 21. Ink 103 is supplied from the ink tank (not
shown in the figures) through ink supply port 31 into first substrate 1 to fill ink cavity 8 and ink chambers 6.
55   Also shown in Fig. 3 is an ink droplet 104 ejected from nozzle 4 during inkjet head drive, and recording
paper 105. As regards the principle of operation of such inkjet head reference is made to the prior art
mentioned above.

Fig. 5 is used to describe the anodic bonding process. As described above, first substrate 1, which is mad from Si, for example, is anodically bonded to second substrate 2, which is mad from Pyrex glass, for example, by applying a 500 ~ 800V DC voltage through electrodes 41 and 42 in a 270 ~ 400°C environment. First substrate 1 is similarly anodically bonded to third substrate 3, which is also made from Pyrex glass, for xampl , by applying a 500 ~ 800V DC voltage through electrodes 41 and 42 in a 270 ~ 400°C environment.

Fig. 6 illustrates the stress acting on substrates 1, 2, and 3 at room temperature after anodic bonding. When the contraction of second and third substrates 2 and 3 is greater than the contraction of first substrate 1, a compressive force acts on and causes diaphragm 5 of first substrate 1 to warp. Conversely, if the contraction of first substrate 1 is equal to or greater than the contraction of second and third substrates 2 and 3, stress will not be applied to diaphragm 5, or if applied only tension acts on diaphragm 5, and diaphragm 5 therefore does not warp. Whether diaphragm 5 warps or does not warp is thus a function of the contraction of substrates 1, 2, and 3. The contraction in turn is a function of the coefficients of linear thermal expansion of substrates 1, 2, and 3. This is described below.

The contraction Δl of the substrates is obtained from the equation

$$\Delta l = \alpha \cdot l \cdot (T_1 - T_2) \tag{1}$$

where α is the coefficient of linear thermal expansion, T_1 is the starting temperature, T_2 the end temperature and l is the starting length. Equation [1] holds true only if α remains constant in the temperature range from T_1 to T_2. Actually, however, α is a function of temperature in most cases. Then, the contraction of first substrate 1 (ϵ_{Si}) and second substrate 2 (ϵ_{Py}) can be obtained by the following equations:

$$\epsilon_{Si} = \int_{T_1}^{T_2} \alpha_{Si}(T) l \, dT$$

$$\epsilon_{Py} = \int_{T_1}^{T_2} \alpha_{Py}(T) l \, dT \tag{2}$$

where T_2 is the bonding temperature; T_1 is the temperature of the operating environment, for example room temperature; $\alpha_{Si}(T)$ is the coefficient of linear thermal expansion of first substrate 1; and $\alpha_{Py}(T)$ is the coefficient of linear thermal expansion of second substrate 2.

As described above, when the contraction ϵ_{Si} of first substrate 1 is equal to or greater than the contraction ϵ_{Py} of second substrate 2, warping of diaphragm 5 does not occur.

The present invention is based on the recognition that by utilizing the temperature dependence of α it is possible to select a bonding temperature T_2 satisfying the following equation

$$\epsilon_{Si} \geq \epsilon_{Py}. \tag{3}$$

In other words, when T_r is the normal room temperature and T_b the temperature for bonding a suitable value for T_b is determined in the following way. First the functions $\alpha_{Si}(T)$ and $\alpha_{Py}(T)$ have to be established such as by experiments. Then a value of T_b satisfying the following relationship is determined:

$$\int_{T_r}^{T_b} \alpha_{Si}(T) \, dT \geq \int_{T_r}^{T_b} \alpha_{Py}(T) \, dT \tag{4}$$

If the thus found temperature T_b is used for bonding a silicon substrate to a glass substrate the relationship [3] will be satisfied.

Fig. 1 is a graph showing the relationship between the temperature and the coefficients of linear thermal expansion, i.e. functions $\alpha_{Si}(T)$ and $\alpha_{Py}(T)$. Pyr x glass shows variation in the coefficient of linear thermal xpansion with different production lots. In Fig. 1, #1 indicates an example of a lot with a relatively high coefficient of linear thermal expansion, while #2 indicates an example with a relatively low coefficient of

5 linear thermal expansion. Equation [3] above is satisfied using Pyr x glass in lot #1 with a bonding temperature of 300°C or greater, and using lot #2 with a bonding temperature of 215°C or greater. Thus, anodic bonding preventing diaphragm warping can be accomplished by using a bonding temperature of 300°C or greater with Pyrex glass lot #1, or using a bonding temperature of 215°C or greater with Pyrex glass lot #2. If the bonding temperature exceeds 400°C, however, tensile stress becomes too great,

10 creating the possibility of diaphragm 5 being damaged. The preferred upper limit of the bonding temperature range is therefore 400°C.

If the Pyrex glass material is more specifically limited to that with the properties of lot #1, a bonding temperature of 270°C or greater can be used because no practical operating problems result with warpage of ±500 Å (±50 nm) when the bonding temperature is 300°C or less. Considering variations or tolerance in

15 characteristics between Pyrex glass lots, the preferred bonding temperature range is therefore 270°C ¯ 400°C. Within this range, a more preferable range is 270°C ¯ 330°C, and is even more preferably 300°C ¯ 330°C. This range of bonding temperatures for Pyrex glass in lot #1 will also satisfy the bonding temperature conditions for Pyrex glass in lot #2. As a result, if the bonding temperature conditions are defined based on a Pyrex glass for which the bonding temperature conditions are in a high temperature

20 range, anodic bonding can be accomplished at the same bonding temperature irrespective of the characteristics of other Pyrex glass lots.

By means of the invention thus described, warping of thin diaphragms formed as part of the first substrate can be prevented, and normal inkjet head operation can therefore be expected, because the first and second substrates, or the first and third substrates, are anodically bonded, and the bonding tempera-

25 ture is set so that the contraction of the first substrate after bonding is equal to or greater than the contraction of the second or third substrates.

It is to be noted that while the invention has been explained above with reference to an inkjet head, it is possible to apply the bonding method of the invention to all devices having similar problems and, particularly, to those having an electrostatic actuator formed by anodically bonding two or more substrates.

30 While the invention has been specifically described with respect to silicon and glass it may be used with other materials as long as these materials have respective functions $\alpha(T)$ for which a temperature T_b exists that satisfies the above relationship [4].

Claims

35

1. A method of anodically bonding a first substrate (1) made of silicon to a second substrate (2; 3) made of glass wherein the thickness of at least a portion of the first substrate is less than the thickness of the second substrate, said method comprising the steps of

   (a) obtaining for a range of temperatures T including room temperature T_r a first function $\alpha_{Si}(T)$ and
40   a second function $\alpha_{Py}(T)$ representing the variation with temperature of the coefficients of linear thermal expansion of the first and second substrates, respectively,
   (b) calculating from the two functions obtained in step (a) a temperature T_b satisfying the relationship

45

$$\int_{T_r}^{T_b} \alpha_{Si}(T)dT \geq \int_{T_r}^{T_b} \alpha_{Py}(T)dT$$

50

   (c) heating the substrates to the temperature T_b,
   (d) applying a voltage between the substrates for a predetermined time while keeping them at temperature T_b,
   (e) removing the voltage, and
55   (f) cooling the bonded substrates to room temperature.

2. A method of producing an inkjet head having at least one ink chamber (6) in communication with a nozzle (4) and an ink supply passage (7), and an electrostatic actuator associated with the ink chamber

6

and constituted by a vibration plate (5) forming a wall of said ink chamber and an electrod (21) arranged opposite to the vibration plate via a gap, said method comprising the steps of:

(i) providing a first substrate (1) mad of silicon and a second and third substrate (2, 3) made of borosilicate glass, each substrate having opposed first and second substantially plane surfaces,

(ii) selectively etching the first surface of the first substrate to form a recess (12) for said ink chamber (6) and an ink supply passage groove (7) connected to the recess,

(iii) bonding the second surface of the third substrate (3) to the first surface of the first substrate (1) such as to cover said recess (12) and groove (7) and seal their edges,

(iv) forming said electrode (21) on the first surface of the insulating second substrate (2),

(v) anodically bonding the first surface of the second substrate (2) to the second surface of the first substrate (1) with said electrode (21) located opposite to the bottom of said recess (12) via a gap, said anodic bonding being performed at a bonding temperature substantially higher than the normal operating temperature of the inkjet head, and

(vi) providing a nozzle opening (4) in communication with said ink chamber (6),

characterized in that step (v) employs the method of claim 1 such that the contraction of the first substrate is equal to or greater than the contraction of the second substrate.

3. The method of claim 2, wherein step (iii) employs the method of claim 1 such that the contraction of the first substrate (1) is equal to or greater than the contraction of the third substrate (3).

4. The method of claim 2 or 3 wherein said temperature T_b is in the range of from 270°C to 400°C.

5. The method of claim 4 wherein the temperature T_b is in the range of from 270°C to 330°C.

6. The method of any one of claims 2 to 5 wherein said gap between the bottom of said recess (12) and the said electrode (21) is formed by etching the second surface of said first substrate (1) prior to step (v) to form a further recess (15) below the bottom of said recess in the first surface.

7. The method of any one of claims 2 to 5 wherein said gap between the bottom of said recess (12) and said electrode (21) is formed by etching the first surface of said second substrate (2) prior to step (iv) to form a further recess and by forming said electrode in the further recess.

8. The method of any one of claims 2 to 7 wherein a plurality of said recesses (12), grooves (7), electrodes (21) and nozzle openings (4) are formed to provide a plurality of separate ink chambers (6) each connected to a respective nozzle opening (4) and a respective ink supply passage with the vibration plate (5) of each ink chamber and the associated electrode (21) forming a respective separate electrostatic actuator.
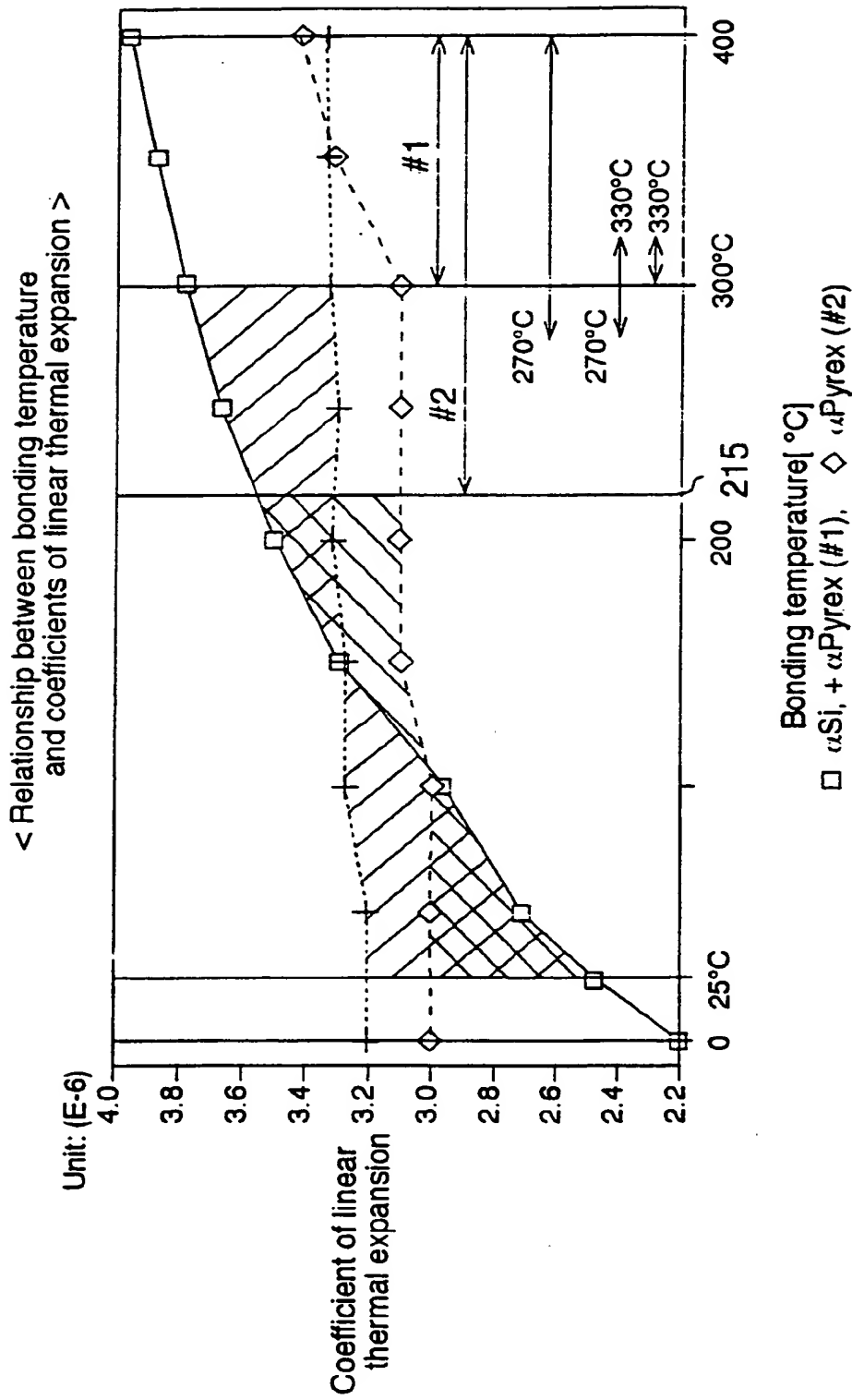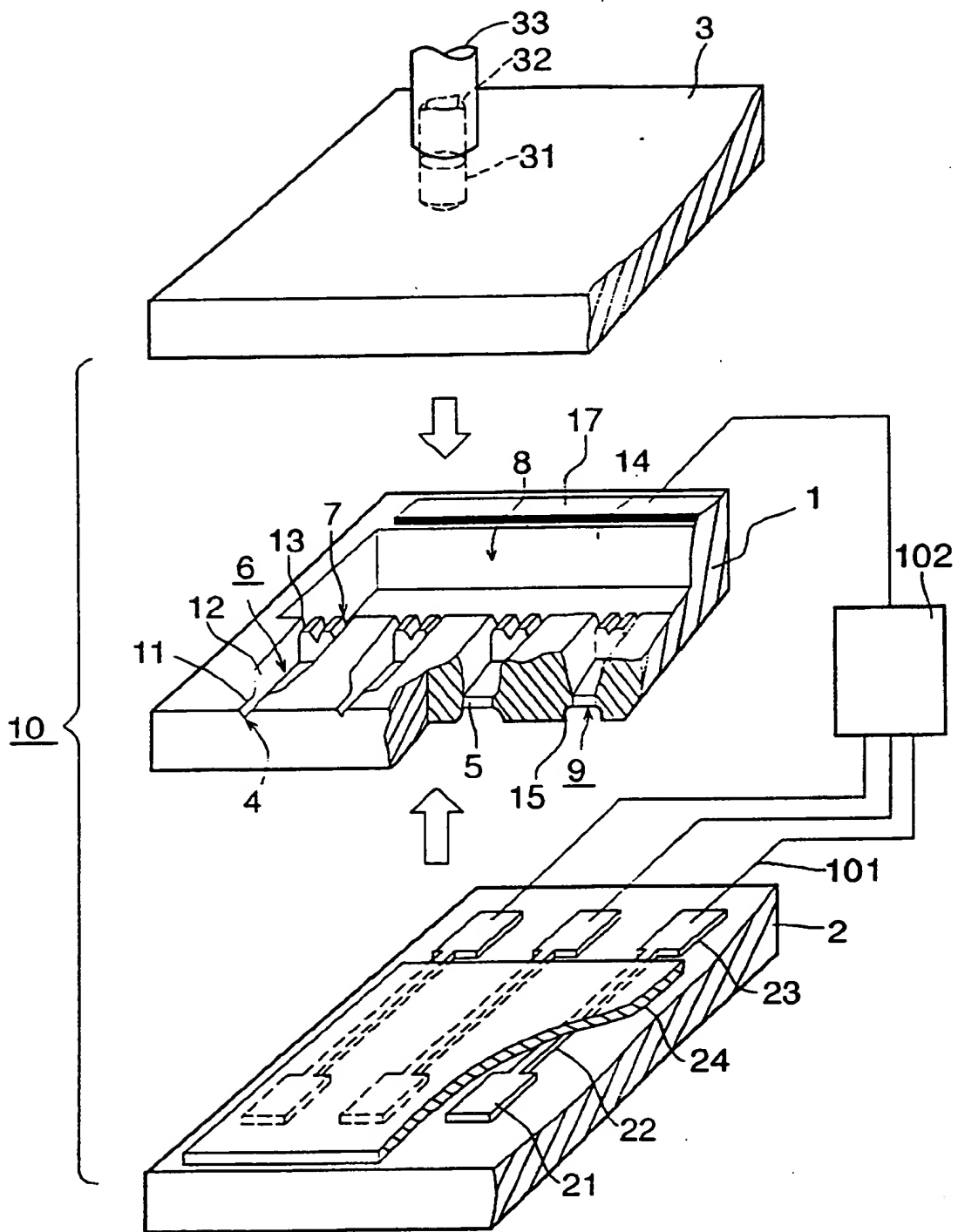
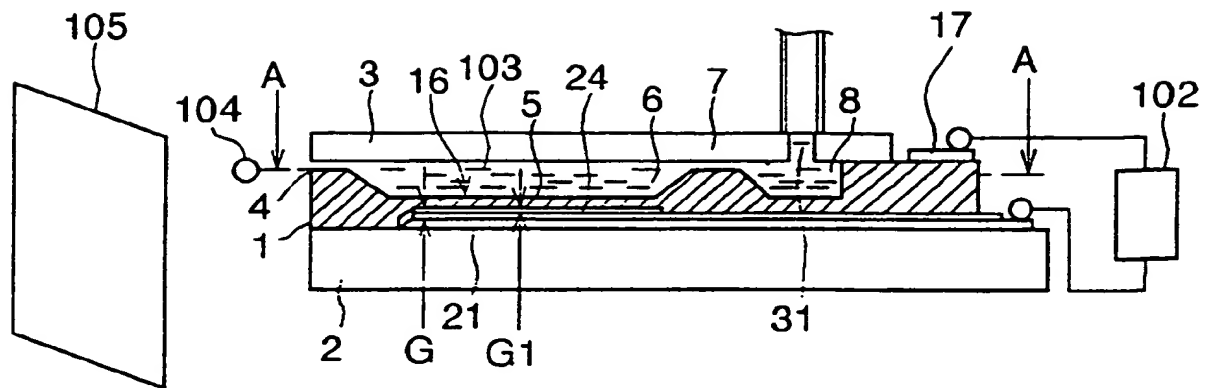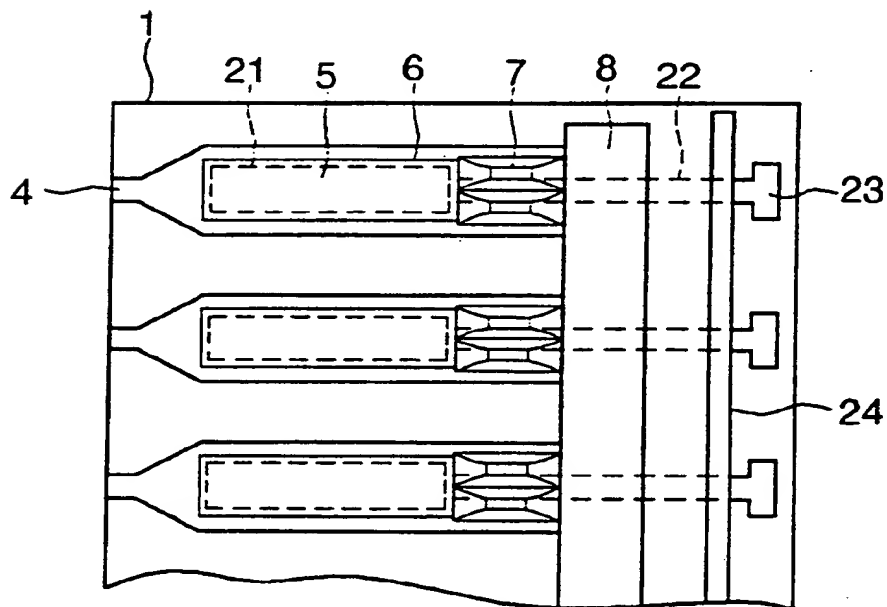< Relationship between bonding temperature and coefficients of linear thermal expansion >

Unit: (E-6)

Coefficient of linear thermal expansion

Bonding temperature[°C]

□ αSi, + αPyrex (#1), ◇ αPyrex (#2)

FIG. 1

FIG. 2

FIG. 3

FIG. 4

FIG. 5

FIG. 6